Climate Requirements for Upper-Air Observations:

The need for a critical re-examination of current activities

Essential to understanding climate change is an ability to unambiguously observe variations and monitor long-term changes. While much has been learned from existing atmospheric observations, it is generally agreed that the historical (and current) upper-air observing system has not adequately addressed climate needs.

Monitoring of the free atmosphere has primarily been undertaken for purposes of weather forecasting, and existing measurement systems all have shortcomings when assessed from a climate perspective. Satellite systems have inadequate vertical resolution and difficulties in continuity as orbits drift and satellites are replaced. The radiosonde network has significant spatial and temporal gaps. Measurement accuracy is in many cases insufficient. Perhaps most challenging, the long-term stability of all the historical observations is seriously compromised by numerous changes in instrumentation and observing methods, severely limiting the utility of the data for understanding climate trends. Because the effects of these changes cannot be unambiguously removed from the data, and because there are no reference measurements against which to compare, the resulting large uncertainty in climate trends undermines our ability to make definitive statements regarding reasons for observed upper-air climate changes.

If climate scientists are to provide definitive policy-relevant information, then it is critical that we learn from our experiences to date. We must establish or modify observing networks so that they meet our scientific and societal needs for robust and unambiguous observations of the atmosphere above the surface.

NOAA and WMO/GCOS have set up a series of workshops to address this aim. This report details the results of deliberations at the first such workshop, held in Boulder, Colorado, in February 2005, which intended to define climate requirements for upper-air observations. The intended audience of the report is the second workshop which will discuss technological and sampling options to meet these requirements. What follows both summarizes the deliberations that took place in Boulder and builds on those discussions, having been vetted by the Boulder workshop participants and other interested parties.

Climate Requirements for Upper-Air Observations

Report of a NOAA/GCOS Workshop, Boulder, Colorado, 8-11 February 2005

December 14, 2005

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This workshop report was prepared by Dian Seidel, William Murray, Peter Thorne and Howard Diamond based on presentations made at the workshop, notes taken by the facilitator team, and subsequent input from workshop participants.

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1. INTRODUCTION

1.1 The Climate Challenge

Definitive climate observations are required to provide the basis for useful climate services and information and sound climate-relevant policy decisions for the benefit of society. Upper-air observations are an integral component of the global climate observing system. Scientists have for decades relied on observations of temperature, humidity and winds from operational radiosonde networks. More recently, satellite observations, offering vastly greater spatial coverage and monitoring of a larger suite of upper-air variables, have also been exploited. Over the past decade, the inadequacy of these systems to fully meet climate requirements has become increasingly clear and the subject of study and scientific debate, including in-depth reviews by both the National Academies (NRC 2000a,b) and the U.S. Climate Change Science Program (under public review at www.climatescience.gov).

The clear message from these reviews is that historical upper-air measurements have been inadequate to unambiguously capture the emerging signal of climate changes aloft. We must learn from this experience and instigate more advanced systems to avoid such problems in the future. Several proposals have been put forward for improved upper-air observations for the 21st century to meet various climate requirements. The Global Climate Observing System (GCOS) has identified a variety of upper-air observational needs for climate and has developed some requirements which are outlined in the GCOS Implementation Plan (GCOS 2004) and Second Adequacy Report (GCOS 2003). However, a comprehensive, scientifically-based set of requirements for upper-air observations for climate has not been developed, and this gap has hindered the incorporation of climate considerations in planning future upper-air observing systems.

This need to develop a sound, science-based set of climate requirements for upper-air observations was the motivation for the NOAA/GCOS Workshop to Define Climate Requirements for Upper-Air Observations. This report provides a summary of the issues discussed at the workshop and the resulting recommendations. The report is *not* a detailed account of all of the workshop presentations and discussions. Readers interested in that information are encouraged to view the presentations that are available online at the workshop website www.oco.noaa.gov/workshop. Instead, the report attempts to bring forward the salient issues and recommendations for the benefit of those who will be evaluating various technological options to meet the requirements in a second workshop.

1.2 Workshop Scope and Integration with US and International Programs

The NOAA Climate Office, the U.S. GCOS Program Office, and the GCOS Secretariat based at the WMO in Geneva, Switzerland, co-sponsored this first workshop hosted by NOAA and the University of Colorado's Cooperative Institute for Research in

Environmental Science in Boulder. The workshop brought together scientists with expertise in the full spectrum of climate activities that require upper-air sounding observations, including:

- monitoring and detecting climate variability and change;
- climate prediction on all time scales beyond that of weather forecasting, ranging from the two-week prediction to seasonal, interannual, and longer time scales;
- climate modeling, including model evaluation and development of parameterizations of physical processes not explicitly included in a model;
- climate process studies including studies of feedback processes;
- reanalysis activities; and
- satellite studies, including calibration of satellite retrievals and radiative transfer studies.

The workshop was also attended by a limited number of participants from the operational atmospheric observing system community and by members of the NOAA Facilitator Cadre, who helped facilitate and document the workshop proceedings.

The intent of the workshop was to develop a set of quantitative requirements (vertical, horizontal, and temporal resolution, long-term stability, accuracy, etc.) in a form consistent with existing NOAA and GCOS standards for articulating observing system requirements. Both the NOAA and GCOS programs recognize that clear, quantitative requirements statements are a first step in defining and implementing observing systems.

The workshop agenda, participants list, and sponsors are included as Appendices A, B, and C of this report. Additional information, including presentations made at the workshop and a series of useful background documents can be found at www.oco.noaa.gov/workshop.

1.2.1 US Activities

US Climate Change Science Program

The Climate Change Science Program (CCSP) integrates federal research on climate and global change, as sponsored by thirteen federal agencies and overseen by the Office of Science and Technology Policy, the Council on Environmental Quality, the National Economic Council, and the Office of Management and Budget. Among the agencies participating in CCSP, several are actively involved in the design and operation of observing systems, including upper-air observations, for climate. The National Oceanic and Atmospheric Administration (NOAA), the National Aeronautics and Space Administration (NASA) and the Department of Energy (DOE) have important ongoing operational and research programs in this area.

NOAA

NOAA's strategic plan articulates four mission goals, one of which is to "Understand Climate Variability and Change to Enhance Society's Ability to Plan and Respond". Performance objectives associated with this goal are as follows:

- Describe and understand the state of the climate system through integrated observations, analysis, and data stewardship.
- Improve climate predictive capability from weeks to decades, with an increased range of applicability for management and policy decisions.
- Reduce uncertainty in climate projections through timely information on the forcing and feedbacks contributing to changes in the earth's climate.
- Understand and predict the consequences of climate variability and change on marine ecosystems.
- Increase the number and use of climate products and services to enhance public and private sector decision-making.

Among the associated strategies for this goal is to "improve the quality and quantity of climate observations, analyses, interpretation, and archiving by maintaining a consistent climate record and by improving our ability to determine why changes are taking place". The workshop directly addressed these objectives and strategies as they relate to upper-air observations, and the recommendations are meant to significantly enhance our ability to achieve the agency's climate mission goal.

Within NOAA this activity falls under the purview of the NOAA Observing System Architecture, which parallels WMO's Rolling Requirements Review. These programs were represented at the workshop to ensure that the requirements are clearly articulated and complete.

1.2.2 International Activities

GCOS

The Global Climate Observing System (GCOS) was established in 1992 and is co-sponsored by the World Meteorological Organization, the Intergovernmental Oceanographic Commission, the U.N. Environment Programme, and the International Council for Science. GCOS is intended to be a long-term, user-driven, operational system capable of providing the comprehensive observations required for monitoring the climate system, for detecting and attributing climate change, for assessing the impacts of climate variability and change, and for supporting research toward improved understanding, modeling and prediction of the climate system. It addresses the total climate system including physical, chemical and biological properties, and atmospheric, oceanic, hydrologic, cryospheric and terrestrial processes. (Source: http://www.wmo.ch/web/gcos/gcoshome.html.). The GCOS observational strategy is based on achieving an optimal balance of satellite and in-situ data and ensuring data are stable enough to allow reliable detection of climate change. It relies on making full use of all available data to achieve a cost-effective global observing system.

GEOSS

The Global Earth Observing System of Systems (GEOSS), supported by more than sixty countries and 33 international organizations, intends to provide an interdisciplinary focus for an integrated international system using remote sensing and in situ systems. When completed, GEOSS will comprise a distributed system of systems that improves coordination of strategies and observation systems; links all platforms: in situ, aircraft, and satellite networks; identifies gaps in our global capacity; and facilitates exchange of data and information. A key provision of GEOSS is full and open exchange of observations with minimum time delay and minimum cost. The upper-air monitoring component of the GEOSS plan with regard to climate is detailed within the GCOS Implementation Plan (GCOS, 2004).

1.2.3 Integration and Community Involvement

NOAA, GCOS and GEOSS all explicitly recognize that climate observing systems do not stand alone. NOAA envisions an Integrated Upper Air Observing System (IUAOS), and GCOS has called for a Reference Network of climate sites providing highly-detailed and accurate observations for robust calibration/validation of more spatially-complete observations as part of a series of networks. The GEOSS has adopted the GCOS Implementation Plan (GCOS, 2004) for climate. These programs will integrate the requirements of the climate community with those of other users of upper-air observations, to allow evaluation of the full suite of requirements and development of optimized and complementary observing systems, including in situ soundings, satellite observations, and airborne and ground-based upward-looking remote sensors.

NOAA and GCOS also recognize that previous efforts to define climate requirements for upper-air observations have laid the groundwork for this workshop (Unninayar and Schiffer 1997, Ohring et. al 2005, NRC 2004, GCOS 2003 and 2004). However, they did not focus solely on upper-air observations and so do not provide sufficient detail to allow consideration of technical options. The main contribution of this workshop was in bringing together a broad spectrum of the climate community to consider, in detail, upper-air requirements previously put forth and to offer refinements based on current scientific understanding.

A key aspect of this activity is that the results (requirements, technical options, and the eventual observing system) will be widely vetted to develop a consensus supported by the scientific community. The web site (http://www.oco.noaa.gov/workshop) for the workshop attempted to provide as much preparatory documentation as possible and will be a conduit for continuing communication with the community on this issue.

1.3 Workshop Approach to Defining Requirements

This workshop was originally planned to focus on deliberations and recommendations for climate requirements in the form of comprehensive “matrices” listing observations of upper-air variables in five areas of climate activity: monitoring and detecting climate variability and change, climate process studies and climate modeling, satellite observations and radiative transfer modeling, and reanalyses of the past climate record, and climate prediction. These matrices are designed by the NOAA Observing System Architecture program to allow comparison of requirements and capabilities so that observing system redundancies and gaps can be identified. However, during the course of the workshop it became clear that moving directly to filling in the matrices ignored the overarching problem of the structure of the observational networks, and the recognition that some aspects of the existing matrix structure were not well suited to climate requirements.

Discussions led to adoption of a revised approach founded on the need first to define a cascading set of upper-air observational networks that would build up from benchmark observations, with accuracy traceable to international measurement standards, through a reference network that would, in turn, anchor a more extensive baseline network that would provide complete global coverage. Over-arching all of these “climate” networks are observations from other instruments which are primarily driven by weather forecasting requirements but can be (and indeed have been) used retrospectively to monitor climate changes.

1.4 Strategy for Moving Forward

Following this initial workshop, a second workshop is planned to examine potential solutions (e.g., instruments, platforms, and deployments) that may be either available or could be developed, in order to meet the requirements which were defined for a reference network, including rough cost estimates. These options will then be presented to relevant agencies for their consideration, more detailed analysis, and eventual implementation. The focus of this ongoing activity will be the instigation of a reference network, with the recognition that this would complement, and support, satellite and existing in-situ observations.   Thus the material that follows in Sections 2 and 3 emphasizes on reference observations.

2. CLIMATE SCIENCE NEEDS FOR UPPER-AIR OBSERVATIONS

To articulate climate requirements for upper-air observations, we must first identify those climate services and climate research questions that depend on these measurements. The details of these will surely change over time as the science questions and policy needs evolve. Hence observations requirements are highly likely to change over time and we must consider the range of plausible future requirements and not solely the current requirements. By gathering a large and diverse group with an interest in climate observations of the free atmosphere, the hope is that they have collectively identified issues and the major requirements both now and in the future; and have critically assessed the performance of the historical observations to answer our current scientific questions.

This section summarizes these issues, incorporating ideas presented by various participants, both formally and in breakout group discussions. It is important to note that, within the broad topic of "upper-air observations" the workshop tended to focus on observations of meteorological state variables (temperature, humidity, pressure, winds) in the troposphere and stratosphere. Some discussions also dealt with profiles of atmospheric constituents, stressing ozone and aerosols. Little attention was paid to regions above the stratopause.

Within the sections that follow we have necessarily had to focus on individual case studies and instrument types to illustrate the range of needs and historical adequacy of the observations to meet these needs. Focus upon particular instrument types or measurement strategies should not be taken to imply that other systems are adequate or that other measurement strategies will not necessarily prove useful. Focus has also tended to be on records that are sufficiently long to answer questions of multi-decadal variability and that have to date had numerous efforts applied to retrieve climate-quality data sets. Hence relatively new strategies such as GPS-Radio Occultation are not discussed in any great detail, although such new strategies are undoubtedly useful and will have to form an integral part of any future comprehensive environmental monitoring system. Likewise data that have not been heavily used to date for climate monitoring such as infra-red satellite measurements and aircraft measurements, are also not discussed in great detail but are likely to prove useful in our future scientific efforts. **Omission of any given instrument or sampling strategy within this section should not be misconstrued as its being judged of limited use for climate applications.**

2.1 Monitoring and Detecting Climate Variability and Change

The problem of monitoring, detecting, and attributing to causes long-term changes in climate has provided one of the most salient arguments for improved upper-air observations in the 21st century. As discussed by several National Research Council reports, scientific assessment reports of the Intergovernmental Panel on Climate Change and the World Climate Research Programme (particularly its programme on Stratospheric Processes and their Role in Climate), CCSP assessment of temperature trends in the lower atmosphere (USCCSP 2005), and the WMO/UNEP Science Assessments of

Stratospheric Ozone Depletion, there is considerable uncertainty in our estimates of trends in upper-air temperature, water vapor and ozone.

The longest record of upper-air observations has been obtained by launching radiosonde instruments, borne aloft once or twice a day by balloons, from a global network of stations. These radiosonde measurements provide a database of atmospheric variables dating back to the 1930's, although coverage is generally poor before the International Geophysical Year 1957-58. However, the radiosonde data record is characterized by many discontinuities and biases resulting from instrument and operational procedural changes, information on which is often poor or non-existent.

Since the 1970s satellite observations have been available, and some have been assembled and reprocessed to create climate records. However, just as the radiosonde record has deficiencies, the satellite data suffer from, among other things: limited vertical resolution; orbit drift, satellite platform changes; instrument drift; complications with calibration procedures; and the introduction of biases through modifications of processing algorithms.

Similar problems have plagued the global network of ozonesondes, which, unlike the radiosonde network, was deployed with long-term trend monitoring in mind. Nevertheless, changes in instruments and algorithms, coupled with inadequate global sampling, have introduced uncertainties into estimates of long-term changes in tropospheric and stratospheric ozone.

The main observational requirements for monitoring long-term upper-air changes are:

- A long-term (multi-decade), stable, temporally homogeneous record so that changes can confidently be identified as true atmospheric changes rather than changes in the observing system or an artifact of choices as to homogenization approach;
- Good vertical resolution, to allow us to discern the vertical structure of temperature, water vapor, and ozone changes, and of changes in the tropopause, which are important signatures of the effects of different human and natural forcings on the climate system.
- Sufficient geographic coverage and resolution, so that reliable global trends, and the regional pattern of changes, can be determined.
- Observational precision finer than the expected atmospheric variations, to allow clear identification of both variability and long-term changes. This requirement is particularly important for water vapor observations in the upper-troposphere and stratosphere, where routine radiosonde humidity observations have been inadequate for climate purposes, due to observational uncertainties that exceed atmospheric variability.

2.1.1 The vertical profile of temperature trends

The regional pattern and vertical structure of atmospheric temperature trends are sensitive to different climate forcing agents and so are key to the climate change detection and attribution problem. However, significant uncertainties in temperature trends have plagued efforts to quantify tropospheric and stratospheric temperature changes. As shown in Figure 1, the range of global upper-air temperature linear trend estimates from a variety of different analyses of satellite and radiosonde data and climate reanalyses is large. In fact our uncertainty in the trends is of similar or greater magnitude than the trends themselves and is poorly characterized.

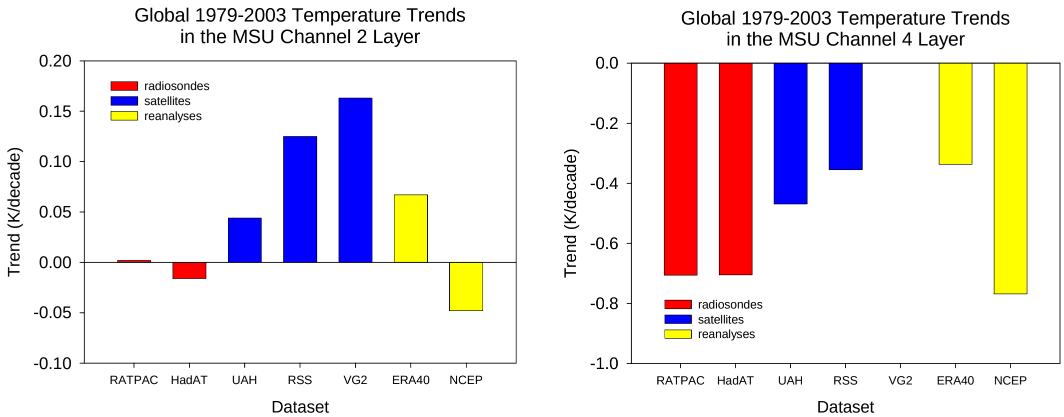

Figure 1. Linear trends in tropospheric (left) and stratospheric (right) temperatures during 1979-2003 (2001 for ERA-40) from different observing systems, and different datasets. Radiosonde and reanalysis temperatures were converted to mimic the satellite MSU channels. The differences among trend estimates are larger than the estimated uncertainties in individual datasets (which are not shown and are poorly quantified), indicating the difficulty of confidently estimating long-term upper-air temperature trends using observations from current systems. Figure courtesy of Dian Seidel.

Because existing observational datasets are not referenced to international measurement standards, and because little has been done to ensure the long-term stability of the measurements, the main challenge is to combine observations from different instruments, locations, and databases to create long-term homogeneous global and regional records. Entirely reasonable choices of homogenization approaches can yield large differences in the identification and adjustment of suspected non-climatic influences, and in the resulting trends for satellite-based records (Thorne et al., 2005) and other records. As illustrated by Figure 2, attempts by different research teams to identify and correct artificial breaks in radiosonde temperature time series do not yield consistent results, which reduces our confidence in the resulting adjusted time series and, consequently, derived trends. Similar arguments will pertain to records gained from other observing platforms.

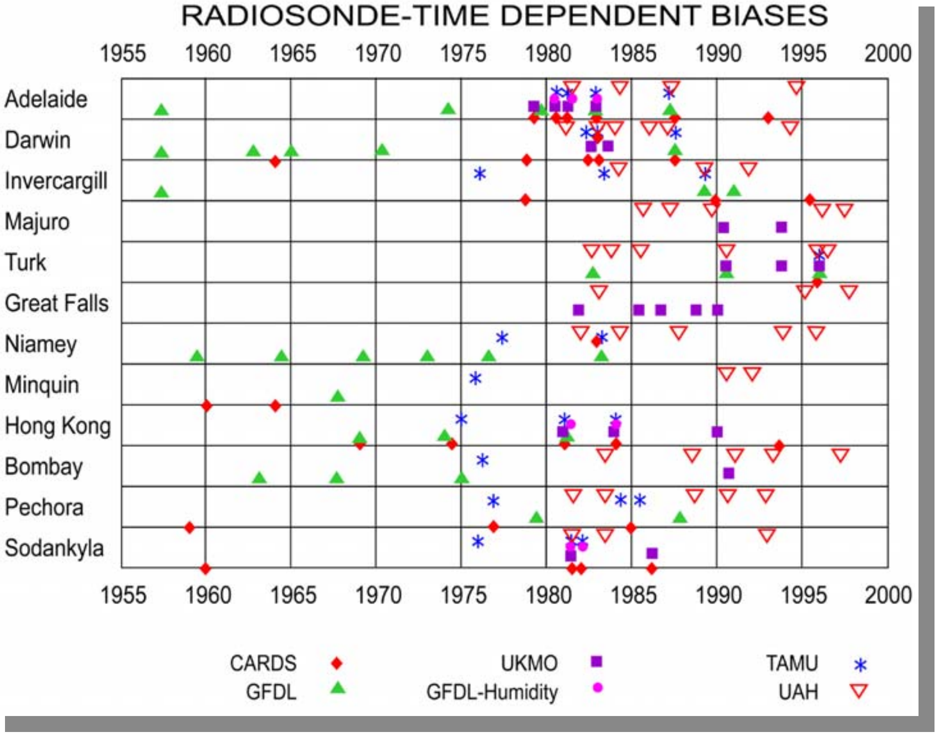

Figure 2. This figure, produced from a 2000 workshop on adjusting radiosonde temperature data for climate monitoring, compares six different teams' adjustment methods for archived data from twelve different stations. At each station, the dates at which the different teams would adjust the data (indicated by a symbol) differ, as do the pressure levels of the adjustment and their magnitudes (not shown). This result underscores the difficulty of creating climate data records using operational upper-air data and the importance of long-term stability in climate observations. Adapted from Free et al. (2002).

The lesson learned from this experience is the critical importance of observations that are well-calibrated and referenced to standards, so that a break in a record from any observing platform can be unambiguously identified and corrected against a stable reference and does not compromise the resulting time series. If this is not feasible for some observations, there must be sufficient overlap when observing systems are changed so that different data segments can be confidently and unambiguously merged to create a credible long-term record. As seen in Figure 3, temperature observations from different types of contemporary radiosondes have biases that vary in a complex fashion in the vertical, and these effects also vary regionally and seasonally (see also Elliott et al., 2002). Similar behaviour is likely to pertain for other instruments and platforms. Furthermore, inter-sonde biases like those seen in Figure 3 will influence and contaminate satellite retrievals, which rely upon the sonde data.

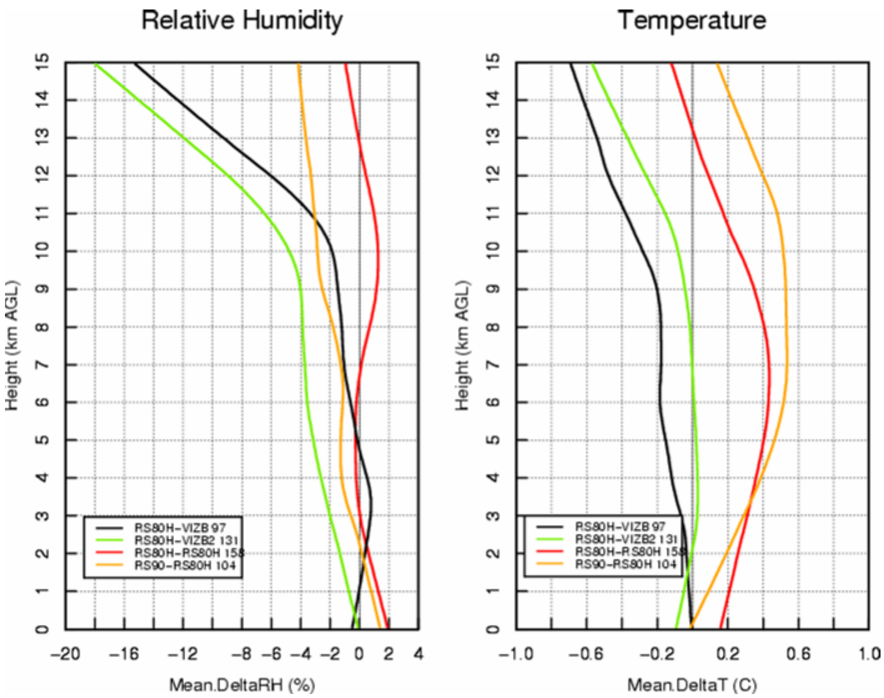

Figure 3. Temperature and humidity "biases" in different contemporary radiosonde types, given by the differences between a given sonde type and the Vaisala RS80H using coincident data collected from two neighboring stations in U.S.A. Figure courtesy of Junhong Wang.

If adjustments are not made at all, or if they are not made perfectly (and artificial jumps, known as interventions, remain in the data record), they introduce uncertainty in estimated climate trends. As shown in Figure 4 for an idealized experiment considering radiosonde temperature records, the rate of errors in trend estimates increases with increasing size of the intervention, and interventions of less than 1 degree C can have significant impacts. It is not unusual for there to be biases of order several degrees C in historical records and for our uncertainty in the resulting adjustments to be of order 1 degree C or more (e.g. Thorne et al., 2005a).

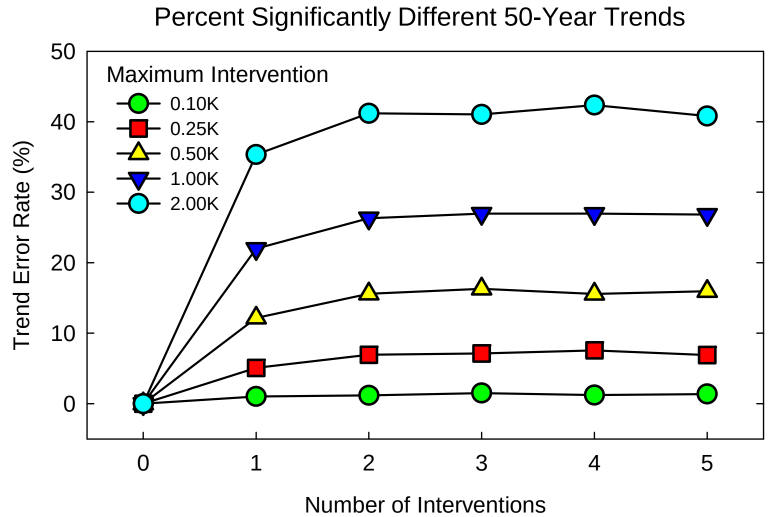

Figure 4. Estimated upper-air temperature trend error rates (frequency of computing a trend statistically significantly different from the true value) when using data with artificial break points, or interventions, introduced by changing instruments or methods of observation. The error rate increases as the maximum size of the intervention increases, and a single intervention does almost as much harm as two or more uncorrelated interventions. These results are based on fifty years of NCEP/NCAR reanalysis data, for levels from the surface to 30 mb, and introducing randomly-timed artificial jumps in the data to simulate instrument changes. Figure adapted from Seidel and Free (2005).

The temporal and spatial resolution of the observations impacts the uncertainty in local, regional and global trend estimates. As the number of observations per month or the number per day decreases, the accuracy of trend estimates decreases and their uncertainty increases. These effects are due to inadequate sampling of diurnal and synoptic scale variations. Similarly, reduced spatial sampling introduces uncertainty in estimates of large-scale temperature trends. As seen in Figures 5 and 6, it appears that a network of approximately 150 stations, with increased density in midlatitudes and polar regions compared with the tropics, would reasonably sample the globe for reliable temperature trend estimates. For humidity, which varies on smaller scales than temperature, more stations are required. These analyses are based upon hypothetical unrealistic (owing to land availability) perfect-world equal-spacing samples where it would be technologically feasible to routinely observe the atmosphere from any given location. The distribution of land masses complicates matters – particularly in the Southern Hemisphere. Despite this caveat, the GCOS Upper-Air Network (GUAN) currently consists of 161 stations that are designed to be as equally-spaced as is possible and so, if it were to be fully functional, would appear to give adequate spatial sampling for monitoring temperature, but not necessarily humidity. Of course, GUAN is a radiosonde sounding network and other observational platforms such as satellites will not suffer from such limitations.

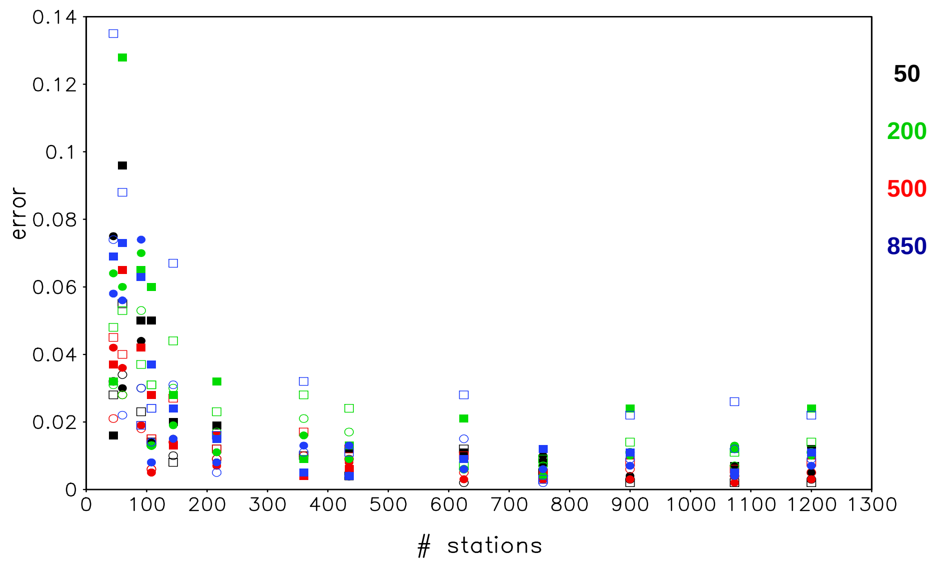

Figure 5. Error in estimated global temperature trends, at four pressure levels shown by the different color symbols, as a function of the number of equally-spaced stations in a global network. Errors are given in degrees C per decade. Adapted from Free and Seidel (2005).

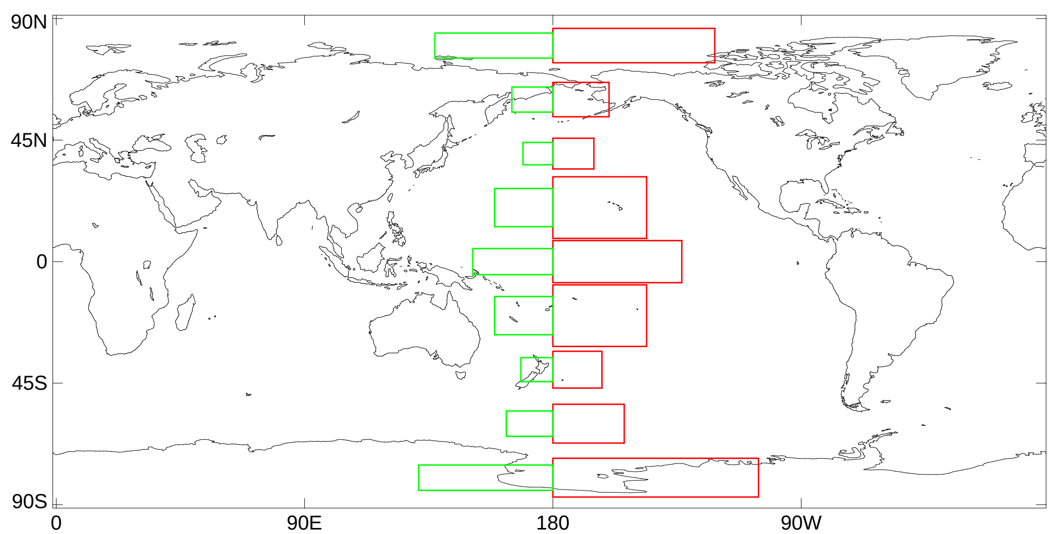

Figure 6: Estimates of the correlation decay distances of inter-annual variability in temperature (red boxes) and relative humidity (green boxes). Each box represents the longitudinal range that can be adequately sampled by a single station for a given latitude band. These estimates have been derived from radiosondes, NCEP/NCAR reanalysis, and version HadAM3 of the Hadley Centre climate model at 500hPa. Only a single estimate is shown due to the high degree of agreement between the observed and modelled

estimates. Note that finer spatial sampling is recommended in mid-latitude regions than in the tropics, and finer spatial sampling is needed for humidity than for temperature. Figure courtesy of Mark McCarthy.

2.1.2 Climatology and variability of water vapor

Water vapor is the most important atmospheric greenhouse gas, but its variability and distribution, particularly the vertical profile, are not well known due to lack of reliable long-term observations in the upper troposphere and stratosphere. Water vapor feedback – the tendency for water vapor concentrations to increase with temperature, thereby leading to an enhanced greenhouse effect and further warming – is thought to be one of the key climate feedback processes (NRC 2003).

It is in the tropical upper troposphere that the strength of water vapor feedback is largest (Figure 7). However, due to poor spatial sampling of radiosondes in the tropics, and poor performance of humidity sensors in the upper troposphere (Figure 8) even the climatology of water vapor there is poorly known. Trends are extremely difficult to estimate, yet they are of critical importance.

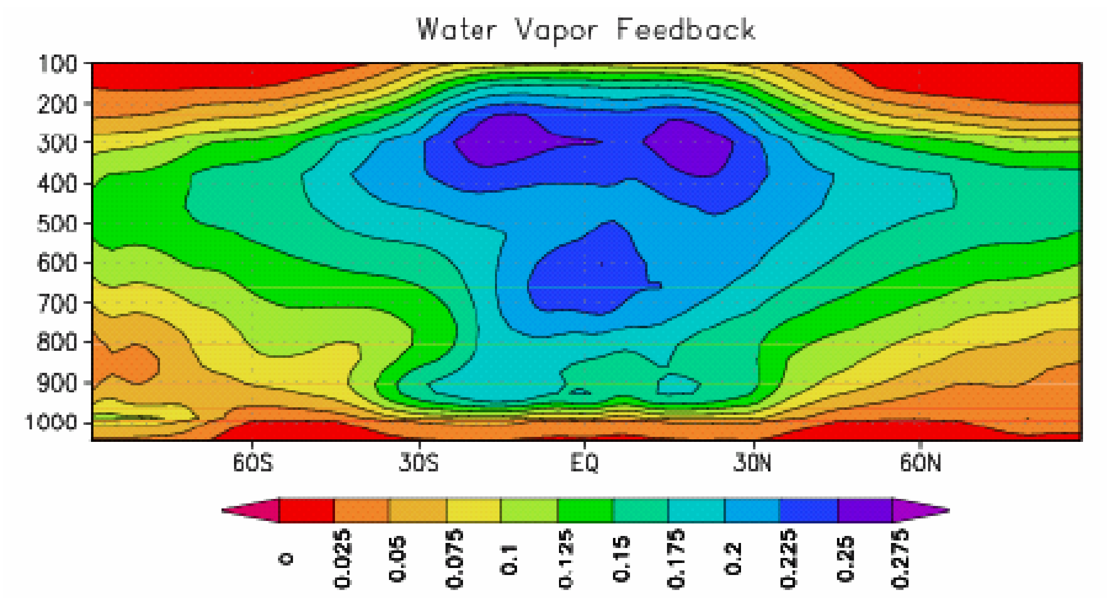

Figure 7. The magnitude water vapor feedback as a function of height and latitude under the assumption of a uniform warming and constant relative humidity moistening in units of W/m2/K/100 mb. Results shown are zonal an annual means. The main contribution to the positive feedback is the increase in water vapor content with increased temperature, leading to increased greenhouse effect and thus further temperature increases. Note that the maximum feedback occurs in the tropical upper troposphere. Figure source: Soden and Held (submitted manuscript).

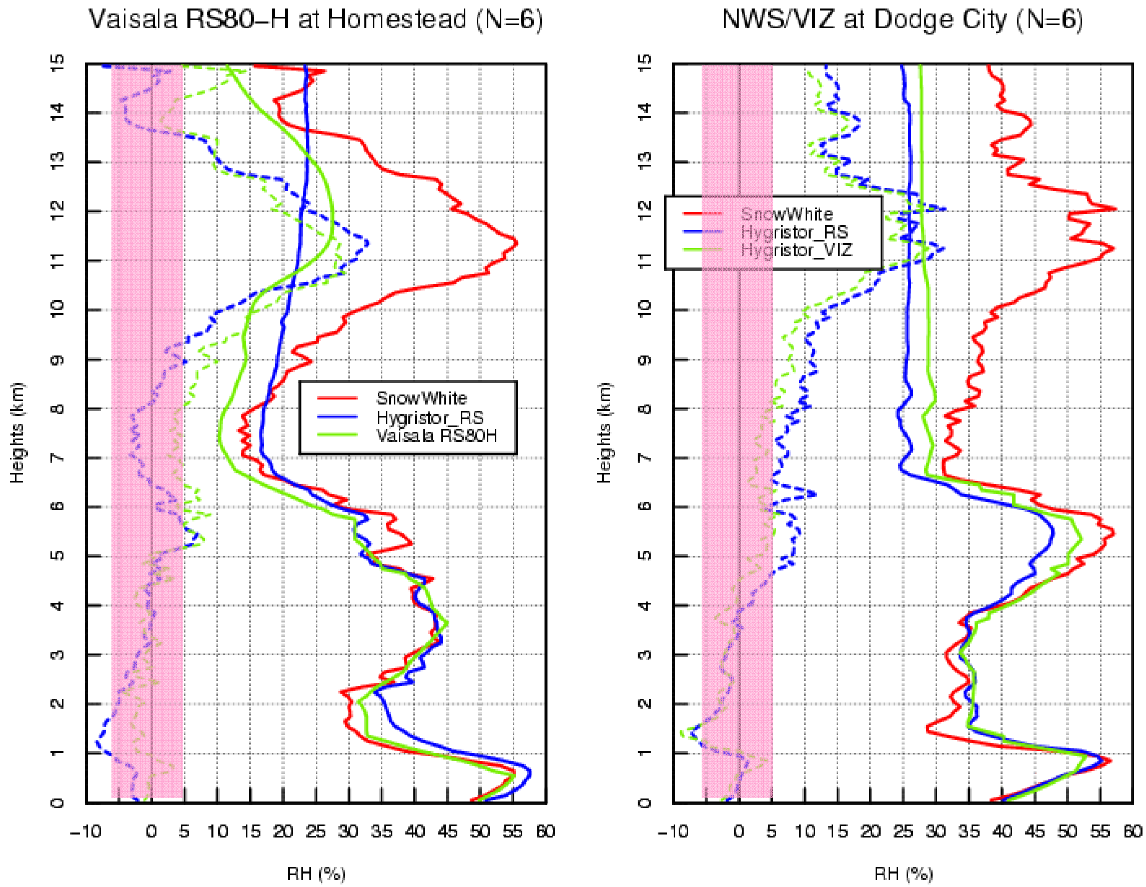

Figure 8. Comparison of standard radiosonde humidity observations with measurements using a more sensitive and accurate humidity sensor, Snow White. Note that the radiosonde humidity profiles show a complete lack of sensitivity in the upper troposphere, and the differences (dashed lines) are larger than the stated measurement uncertainty (pink shading) at altitudes above about 5 km. Figure adapted from Wang et al. (2003).

In addition, the important radiative and chemical effects of water vapor changes in the stratosphere motivate the need for observations there. To date, long-term observations have been made at only one site (Boulder, Colorado), and then only once per month, although a second site (Lauder, New Zealand) has recently started to take similar observations. Expansion of this network to include the tropical and polar regions of both hemispheres would be a significant advance in our understanding of stratospheric water vapor variations.

Water vapor can alternatively be retrieved from satellites from: IR sensors on polar orbiters; SSM/I (Special Sensor Microwave/Imager), MLS (Microwave Limb Sounder), and AMSU-B Microwave sounders; or from GPS radio occultation (in the lower troposphere, and temperature above this region). To date there have only been limited attempts to retrieve long-term water-vapor records from satellites in the infra-red. Retrieval to a geophysical parameter such as temperature or humidity is more complex than is the case for using MSU channels to derive temperature records. More concrete efforts have been made to derive records from the microwave sounders and suggest great promise. However, as for temperature records greater efforts are required to comprehensively understand the uncertainty in satellite water vapor records. GPS radio occultation promises robust monitoring, but is to date too short a record and like data from all sources may have as yet unidentified problems associated with it.

2.1.3 Structure of and changes in tropopause characteristics

Interest in the tropopause has grown significantly in recent years. Two prime motivations are the potential relationships between tropopause characteristics and both ozone and water vapor changes in the stratosphere, and the potential use of the tropopause height as a sensitive indicator of climate change (Santer et al. 2003). High vertical resolution soundings are needed to adequately identify the tropopause location and structure, particularly in the mid-latitudes where winter tropopause over-folding can cause multiple tropopauses and associated stratosphere-troposphere mixing. As shown in Figure 9, a reanalysis dataset, with relatively low vertical resolution, does not reveal the double tropopause structure seen in a higher resolution reanalysis and GPS radio-occultation data. Vertical resolution finer than 500 m is needed to resolve these structures, and even finer resolution is required to detect projected multi-decadal changes on the order of 100 m in tropopause height.

2.1.4 Changes in the vertical profile of ozone, aerosols and other atmospheric constituents

Because changes in trace gases and constituents can have large impacts upon the climate, it is important to understand the vertical structure of the composition of the global atmosphere. Variations in trace gases can significantly impact the radiative emission spectrum of the atmosphere which can affect satellite brightness temperature retrievals and our interpretation of these as meteorological variable proxies. An extensive suite of constituent measurements is required to adequately address these issues. Ozone and aerosols received the most attention at the workshop.

Significant work has already been done in developing measurement requirements related to atmospheric composition (IGACO, 2004; GAW, 2003), and the community has recognized the need for an integrated global observing strategy that includes satellite, aircraft, and ground-based systems using remote sensing and in situ techniques.

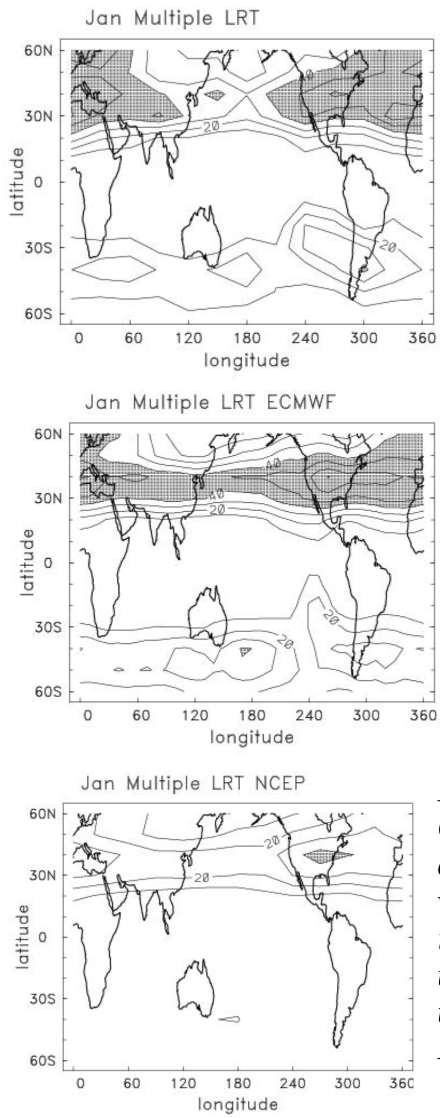

Figure 9. The frequency of double tropopauses in GPS data (top) and in data from ECMWF (middle) and NCEP/NCAR (bottom) reanalyses. The poorer vertical resolution of the NCEP/NCAR data gives an inaccurate view of the tropopause, which underscores the need for high vertical resolution to identify tropopause characteristics. Figures courtesy of Bill Randel, from a manuscript in preparation.

Networks currently exist for measuring atmospheric composition. These include the Global Atmosphere Watch, the Network for the Detection of Stratospheric Change, and the Southern Hemisphere Additional Ozonesondes network. But these require expansion in both spatial and temporal density. Planning efforts for measurements of atmospheric aerosol properties have resulted in detailed requirements and recommendations. Clearly, in creating optimal climate monitoring strategies it is important that we make efforts to synthesize climate monitoring efforts with these other efforts. There would be undoubted benefits for all concerned.

2.2 Prediction of Climate Variations

There are continuing efforts to both predict future climate variations and reanalyze historical variations, on time scales ranging from just beyond the range of weather prediction to multi-decadal. With advances in Numerical Weather Prediction these will become increasingly skillful regardless of changes made to the observing system. One important difference for the climate prediction problem is that unlike for weather prediction, which is an atmospheric initial value problem, predictions of climate variations are primarily based on atmospheric boundary conditions, which may be related to the land or sea surface characteristics, solar changes, changes in the stratosphere, including changes in volcanic aerosol loadings, changes in trace gases, and changes in snow and ice cover.

Atmospheric variations are dominated by a few large-scale modes such as El Niño-Southern Oscillation, related decadal changes in the Pacific, and annular modes in both the Northern and Southern Hemispheres (Thompson and Wallace, 2000). Long-term climate changes may both modulate these and be affected by them.

Specific climate prediction requirements for upper-air observations have not yet been well studied. Carefully designed observing system simulation experiments may help better define requirements. But the state of the science of climate prediction is rapidly evolving, and observations are not the sole factor limiting climate prediction skill.

2.3 Reanalyses of climate change

NWP analyses are not usable for climate studies as they suffer from temporal inhomogeneities due to the continual changes in the model and analysis systems needed to improve weather forecasts. To reduce the impact of such changes, reanalyses of the historical observational record using a constant model assimilation system have been performed in the US, Japan, and Europe. The products of these reanalyses have proven to be among the most valuable datasets for climate studies ever produced, even though they have major shortcomings. An upper-air climate analysis system will necessarily include periodic reanalyses, since both the observing system itself and the analysis technology and science will progress. The description and understanding of climate variability and change will depend critically on progress in improving the observational database, observing systems and analysis systems.

Reanalyses require sufficient horizontal resolution of the observations to allow unambiguous analysis of the winds and thermodynamic structure of the atmosphere. As seen in Figure 10, historically two major reanalyses (ERA40 and NCEP/NCAR) show good agreement regarding the manifestation of the Northern Annular Mode, but they differ regarding the Southern Annular Mode. This uncertainty in the Southern Hemisphere is likely due to inadequate historical spatial sampling by the global radiosonde network, particularly prior to the advent of satellite monitoring. This result demonstrates the degree to which reanalyses have historically depended upon the input data sets, and underscores the importance of in situ observations in anchoring satellite observations, which at least historically provide better geographic coverage but poorer vertical resolution than the radiosonde data.

At a minimum, credible analyses of atmospheric circulation variations are needed, and these require observations with sufficient spatial resolution and fidelity to identify patterns reliably. In Figure 11, it is clear that such a density of observations has not historically been available for the Southern Hemisphere, where the climatological storm tracks show important differences between two reanalyses. The better agreement in the Northern Hemisphere suggests that the historical observations may be sufficient to constrain the reanalyses there.

It is important to stress that the assimilating model being used in a reanalysis system has been developed primarily for short-term weather forecast processes. It is designed specifically to minimize the effects of random errors in the observations (e.g. a rogue sonde) by minimizing an effective cost-function which is some weighted mean of all available observations and an initial background field taken from a previous forecast. With improvements in observational networks and the incorporation of 4D-var assimilation these are undoubtedly improving and will become more realistic but will nonetheless still depend on efforts made to screen the input data. From a climate perspective however, the minimization of error at a given time-step is not a sufficient constraint to gain a climate-quality reanalysis that retains long-term trend fidelity. In climate we are primarily interested in this long-term continuity (e.g. Section 2.1). It is clear that for the historical reanalyses gross-changes in the observing networks (e.g. introduction of satellites) have caused large scale changes. We strongly believe that it would be naïve to assume that the future observing system will remain “stationary” going into the future and that reanalyses will be able absolutely to cope with such biases unless there are changes to the observational network design. To date reanalyses have shown a strong dependence on the observing system and its changes over time, and it remains a challenge to fully bias correct for such changes. An adequate observational reference network is needed for such a purpose.

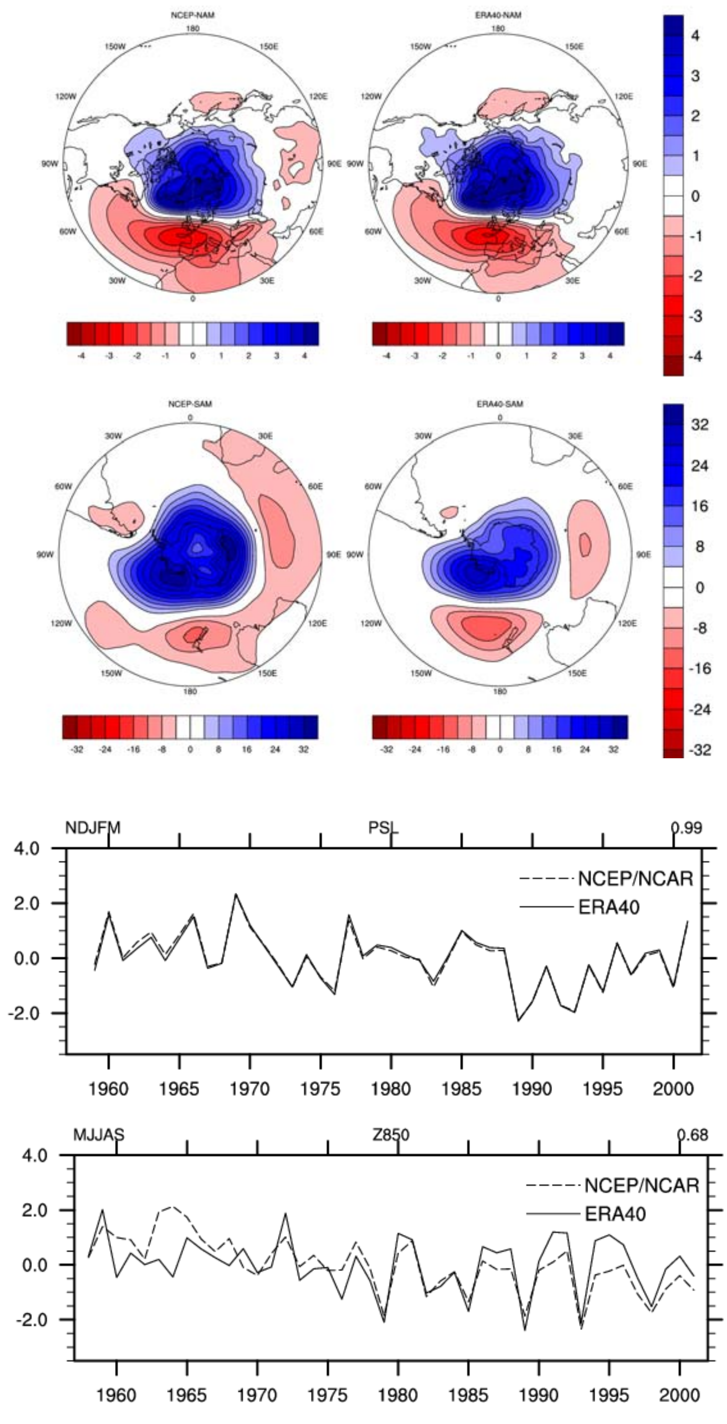

Figure 10. Depictions of the Northern (top map and top time series) and Southern (bottom map and time series) Hemisphere annular modes, based on ECMWF (ERA40) and NCEP/NCAR reanalyses. These large-scale modes account for much of the variability of the climate system, particularly in winter. Note the better agreement, for both the spatial pattern and time variations, in the Northern than in the Southern Hemisphere, due to the denser network of observations there. Figure courtesy of Jim Hurrell, adapted from Quadrelli and Wallace (2004).

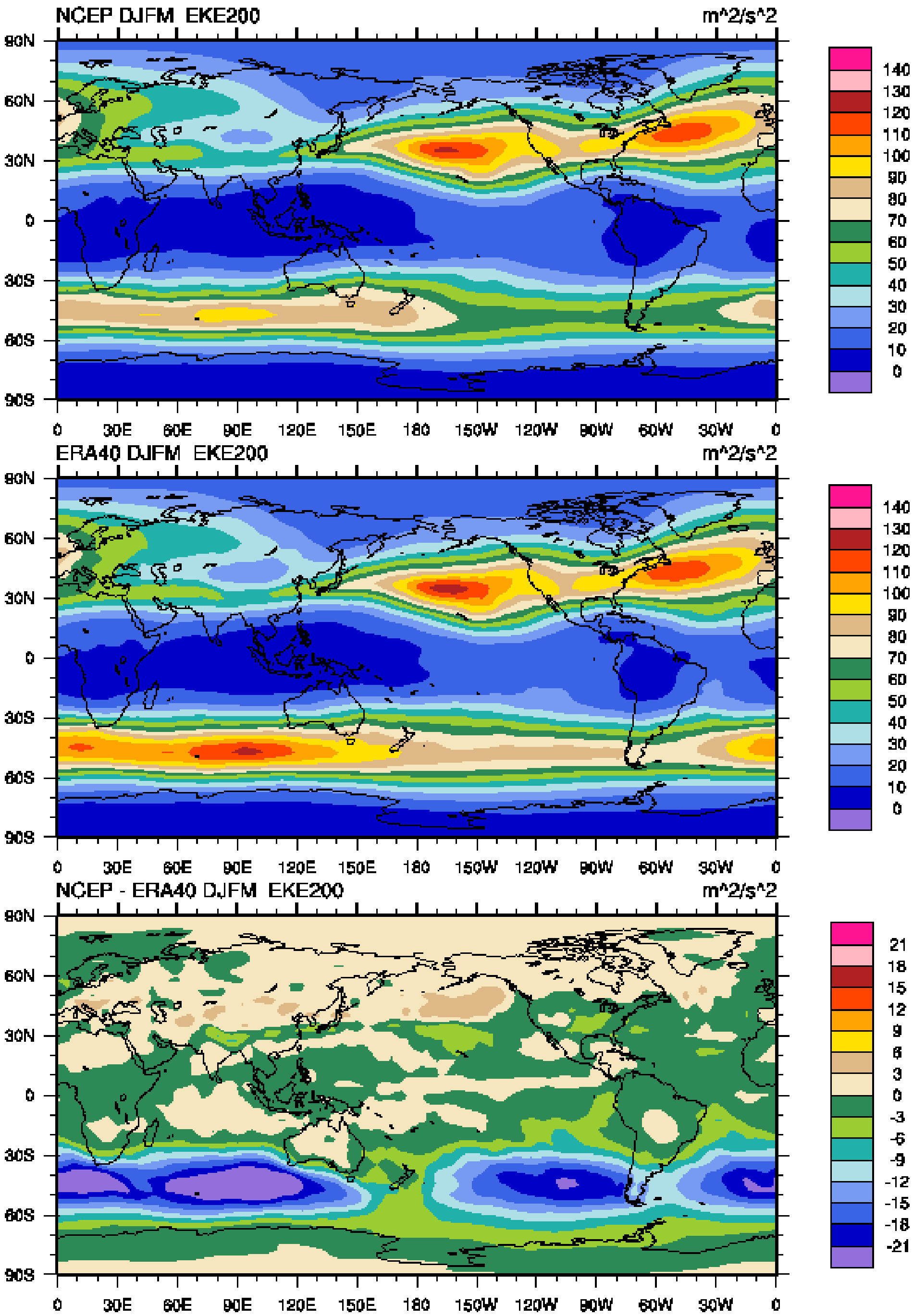

Figure 11. Climatological storm tracks, as seen in 200 hPa eddy kinetic energy fields from ECMWF and NCEP/NCAR reanalyses, and their differences. Regions of high eddy kinetic energy are interpreted as storm tracks. The poorer agreement in the Southern Hemisphere is due to the sparsity of the radiosonde network there. Figure courtesy of Jim Hurrell.

2.4 Understanding Climate Feedbacks and Processes and Improving Climate Models

Projections of climate change in the coming decades and centuries depend on global climate models. The realism of these models, and hence the credibility of climate projections, depends on their representation of climate processes operating over a wide range of space and time scales. These processes, particularly those involving positive or negative feedbacks, determine the response of the climate system to climate forcing agents.

Upper-air observations play a key role in research to improve the reliability of climate models in two ways. First, model simulations are compared with observations to determine the model's ability to simulate the past climate and its variations. This includes both comparison of individual climate elements and comparison of the relationships among different elements involved in particular feedbacks. Second, process studies involve analysis of observations to determine whether model parameterizations accurately portray the effects of processes that cannot be fully resolved by models and to develop new parameterization methods. Clearly if our observational records retain significant biases then any such comparisons will be sub-optimal and could, in extreme cases, lead to erroneous conclusions as to model realism.

Water vapor observations are perhaps the most critically needed observations for improving climate models and their projections of future climate. As shown in Figure 12, climate sensitivity (the magnitude of warming associated with a given change in radiative forcing) depends very strongly on the strength of water vapor feedback. This feedback is strongest in the tropical upper troposphere, where measurements are sorely lacking (Section 2.1.2).

The importance of observations at high temporal frequency to resolve variations on diurnal to interannual scales was stressed. For analysis of feedback processes, simultaneous and collocated observations on multiple space and time scales are needed, and the priority variables are tropospheric temperature, tropical upper-tropospheric water vapor, low cloud cover, and top-of-the-atmosphere radiative fluxes.

The requirement for collocated simultaneous observations can be met by spectrally-resolved satellite observations. As shown in Figure 13, infrared radiance changes in various wavelength regions correspond to changes in temperature at the surface and in the free atmosphere, water vapor, ozone, etc. Radiance data can be used for climate process studies by comparing observations directly with model-simulated radiances.

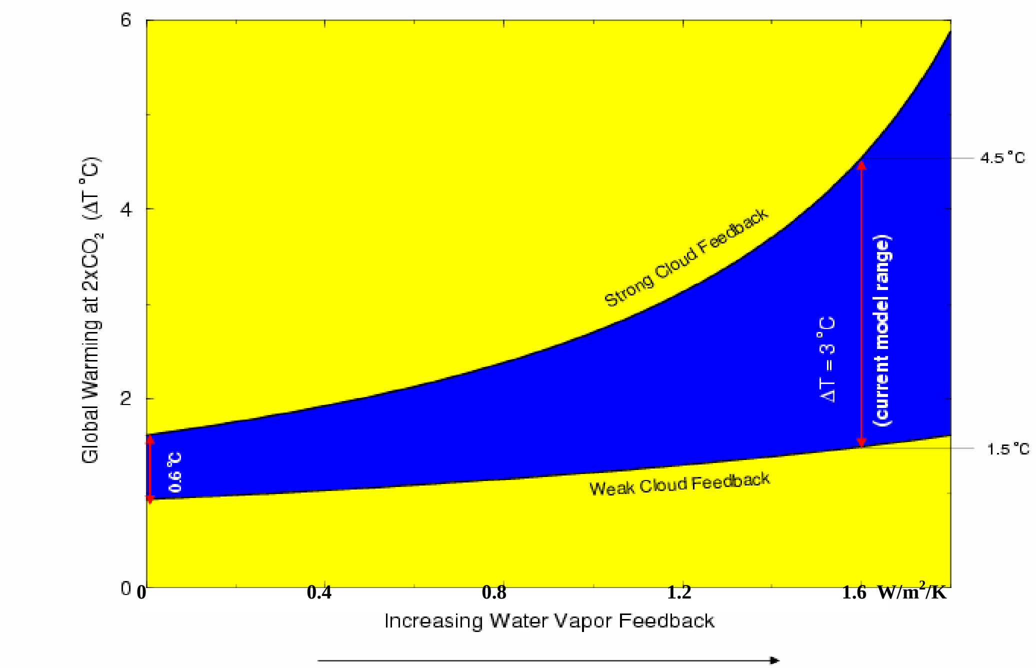

Figure 12. The dependence of climate sensitivity (global surface temperature increase associated with a doubling of atmospheric carbon dioxide) on water vapor feedback. Uncertainties in water vapor feedback are a key element of overall uncertainty in climate sensitivity and hence in climate change projections. Uncertainties in the strength of cloud feedback are also important, particularly for high values of water vapor feedback. Figure courtesy of Brian Soden.

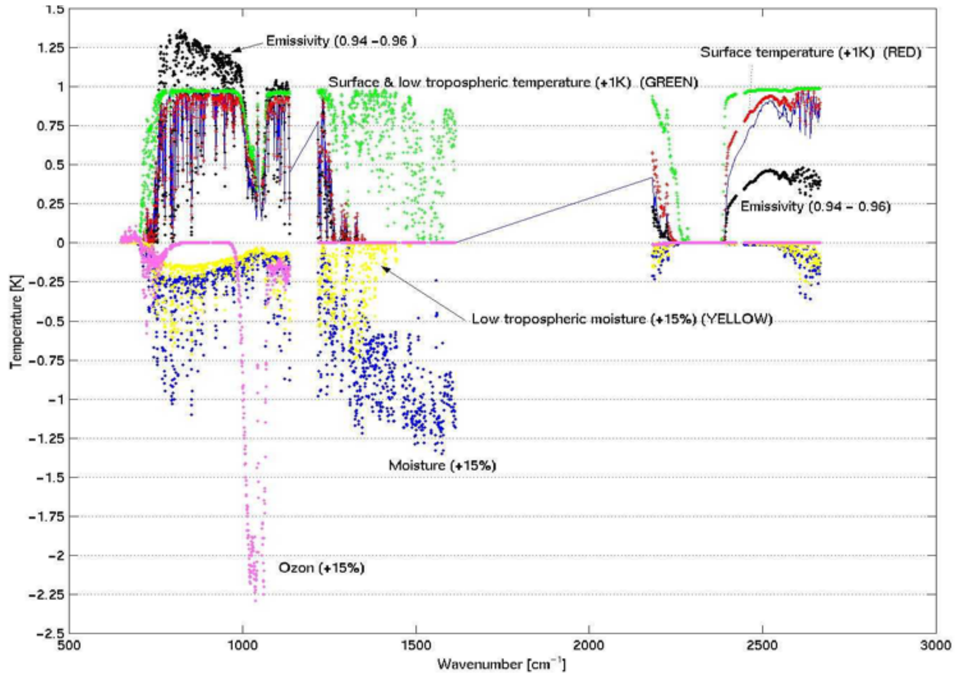

Figure 13 Changes in infrared radiances (brightness temperatures) associated with various atmospheric and surface changes, demonstrating the utility of spectrally-resolved infrared radiance observations. The figure shows the effects of selected climatic changes (e.g., ozone, moisture, temperature, emissivity) of a given magnitude on infrared brightness temperatures. Figure courtesy of Mitch Goldberg.

To perform such studies in "radiance space" requires radiative transfer models to convert between meteorological and atmospheric constituent variables and satellite-recorded radiances. Uncertainties in radiative transfer models contribute to uncertainties in observations of state variables and hence climate models. To reduce these uncertainties in situ profile observations of meteorological state variables must be compared with simultaneous atmospheric radiation measurements from satellites. Thus in situ observing systems complement remotely sensed data and improve their utility for climate work. Efforts to date have been inadequate; comparisons have generally been to a random assortment of sonde types flown within a specified time window of satellite overpass. The variable times of observation, range of sonde types, and use of only a single vicarious data source render the problem under-constrained.

3. AN APPROACH TO OBSERVING THE UPPER ATMOSPHERE FOR CLIMATE

Before outlining our proposed approach, it is worth revisiting the zero-order question of whether current observations are good enough. A question that has repeatedly been asked during the writing of this report is: aren't the current observations sufficient? Or, put another way: you've only shown that historical observations have been insufficient, so why should we spend more money on future observations? These questions have arisen primarily from individuals with expertise in NWP and real-time monitoring, and need to be taken seriously.

Whilst it is undoubtedly true that given the richness of data coming online we will almost inevitably reduce our ambiguity in future changes regardless, the monitoring still answers entirely to operational requirements. Although there are climate monitoring principles, in practice these are rarely followed as operational requirements take precedence. As outlined in Section 2.1, for the climate problem what is of paramount importance is continuity of measurements: we need to be able to seamlessly stitch together records from a range of observational measurements. So, even if we have more data from more systems than ever at our disposal we still require an observing system architecture that allows us to simply and unambiguously construct homogeneous records from this data.

Clearly, based upon discussions in Section 2, a continuation of present observing strategies into the future will not be adequate to answer the major scientific and policy-relevant questions facing the climate science community.

3.1 A System of Systems

Workshop discussions on the overarching structure suitable to provide the complete suite of upper-air observations needed for climate purposes settled on a concept of a **"cascade"** of four sets of observations: **benchmark observations**, a **reference network**, a **baseline network**, and a **comprehensive network**, as depicted schematically in Figure 14. The benchmark measurements would be limited to a small set of variables, initially just temperature and water vapor, which can be measured with techniques clearly traceable to international standards. They would provide a solid "core" for a larger reference network. This reference network would still be limited to a relatively small number of stations, perhaps 30-40, that would provide continuous, stable, high-quality measurements of a larger number of variables. The reference network would, in turn, provide anchor points for the baseline GUAN radiosonde network and the global comprehensive network that would contain multiple data types and provide the detailed spatial resolution necessary to relate climate change and variability to human activities and the environment. The comprehensive network would be comprised of a variety of different measurement systems, the data from which would be assimilated into global and regional analyses for climate studies.

Different networks will be useful for answering different specific scientific questions, but all of the networks are required for unimpeachable, unambiguous climate monitoring. The comprehensive network is required to provide observations with spatial and temporal resolution to make policy decisions and conduct research relevant to individual's lives. The baseline GUAN network provides coverage sufficient to monitor hemispheric and global scale changes essential to ascertaining the fidelity of climate models at the largest space and time scales and unraveling the true causes of climate change. And the reference and benchmark observations provide the ground-truth and research opportunities that have previously been denied us and led to the scientific uncertainties outlined in Section 2. Therefore it makes more sense scientifically to derive requirements by network type than by spatial and temporal resolution as has traditionally been the case for defining real-time NWP monitoring requirements and has served that particular community well. Here we expand on the rationale for each of the networks, and specify requirements for benchmark observations and the reference network.

At present, a continued focus upon each of these networks is not likely to deliver meaningful progress on any one of them in the short term. To focus upon attainable goals at the second workshop, the steering committee of the overall process and the sponsors of the first workshop advocate focusing upon instigating the reference network. There are a number of reasons:

- The need for a reference network is articulated in the GCOS Implementation Plan as being of the highest priority, and this plan has been adopted by GEOSS.
- It appears that technology already exists to initiate a reference network, but requirements, protocols, management and funding are currently lacking.
- Efforts have already been undertaken by GCOS to implement a larger baseline GUAN network. More comprehensive networks have real-time weather monitoring as their primary aim. Although these do not mean climate requirements should not be incorporated within these monitoring efforts, it is questionable what further benefit there might be in continued scrutiny of these issues at this time.
- The need for benchmark observations, traceable to international standards and capable of ensuring reliable information on long-term climate change, is clear. However, it is felt to be premature to initiate a process to determine technical options for deploying a benchmark observing system operationally. Research is needed to determine unambiguously the capabilities and limitations of the proposed technologies and questions remain as to the optimal way to monitor the entire atmospheric column and whether this can realistically be attained by a single instrument.

Hence in the subsequent sections we briefly summarize the workshop discussions on the benchmark and comprehensive networks, but focus on reference network discussions that were undertaken at the meeting and at subsequent forums, as well as incorporating feedback from participants and the wider scientific community.

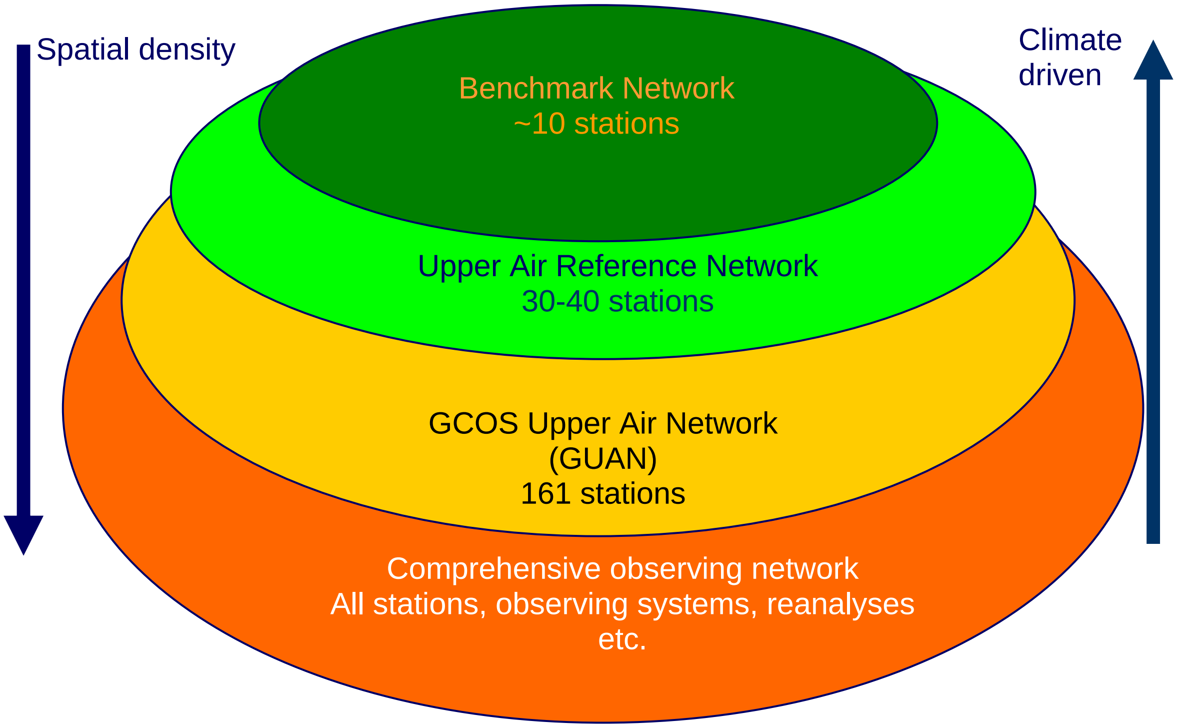

Figure 14. The "cascade" of upper-air observations envisioned by the workshop.

3.2 Benchmark Observations

Creation of a truly benchmark network is probably impossible at the present standards of technology. However, this does not mean that this should not be strived for. Current observations have both known and unknown biases which are very difficult to unambiguously correct. The credibility of information on future climate trends would be greatly enhanced if it were based on continuous, stable observations whose accuracy is traceable to international standards. Current systems may start with calibrations that are traceable to international standards in a laboratory setting, yet these are not always maintained over the lifetime of the system and may not even be strictly applicable when it is operating in the real atmosphere. A benchmark system, comparable to the atmospheric carbon dioxide measurement from Mauna Loa, is therefore highly desirable.

In practice, the number of benchmark variables measured would be limited, at least initially, to those most important to the long-term monitoring problem. There are very many advocates of GPS radio occultation to act as a benchmark system for temperature and water vapor. GPS RO can be obtained with good estimates of absolute accuracy, because the basic measurement is a delay time. However, the workshop and subsequent expert reviews of the report have revealed differences of opinion regarding the readiness of GPS RO to serve as a baseline observing system.

A number of assumptions must be made in converting these SI traceable time delay measures to the atmospheric state variables of interest, and sensitivity to first-guess is non-negligible. (These factors are undoubtedly less of an issue than for polar-orbiter measures in the IR and microwave bands; but unlike GPS these are not being advocated as benchmark or even reference network measures.) There is also the significant issue that these are measures of opportunity in both space and time which yields problems of analysis (and interpretation as a benchmark measure in the strictest sense of the word) vis-à-vis a potential static benchmark. Furthermore, GPS-RO interpretation becomes more difficult in the lower troposphere where both temperature and water vapor are confounding effects upon the refraction index. Any benefits would have to address and out-weigh these issues.

A second option is to measure temperature and humidity from in situ sensors whose calibration is enhanced to meet the standards of a benchmark observation. A further option is to combine a number of high-quality measures from a combination of sources, such as high-spectral resolution IR sounders, GPS-RO and reference sondes. All options at present are both unproven and have problems in interpretation as benchmark measures due to: measurement strategy; uncertainty regarding future continuity of measurement technology; and capability to monitor in a consistent manner throughout the atmospheric column.

The table below presents requirements for benchmark observations of temperature and water vapor. The sense of the Boulder workshop was that benchmark observations of this sort are the best option for unimpeachable long-term monitoring data. Linkage of benchmark observations to reference network observations would provide an "anchor" for the latter, so that the much richer suite of observations from the reference network could be more usefully blended to form a comprehensive picture of climate processes.

Variable	**Geographic Coverage**	**Vertical Range**	**Vertical Resolution**	**Accuracy**
Temperature	Global	0 km to mesopause	0.1 – 0.5 km	0.1 K
Water Vapor	Global	0 – 30 km	0.2 – 1.0 km	0.1 %

3.3 Reference Network

The concept of a reference network augments the GCOS Upper-Air Network (GUAN). The establishment of this network is articulated in the GCOS Implementation Plan (GCOS 2004), which has been adopted by GEOSS. The principal aims of this network are to provide:

- long-term high quality climate records
- anchor points to constrain and calibrate data from more spatially-dense global networks (including satellites),
- a larger suite of co-related variables than can be provided as benchmark observations.

The key property of a reference network as agreed at the workshop is deliberate redundancy of measurements. It is important to stress that a reference network is much more than a set of high quality radiosondes. Instead, the aim of the reference network is to fully characterize the properties of the atmospheric column at a small set of sites. Measurement redundancy, whereby the same atmospheric property is measured by at least two separate complimentary instruments (e.g. a radiosonde and a ground-based GPS sensor for humidity) simultaneously, will provide strong constraints on instrument biases and properties across a range of timescales from synoptic to inter-annual to enable explicit calculation of these effects. The capability of reference sites will increase with the level of measurement redundancy. A critical aspect of this measurement redundancy is active monitoring so that problems can be identified and rectified in real-time.

As a minimum requirement, the network should consider those variables identified as Essential Climate Variables in the GCOS Adequacy Report and the Implementation Plan, and identified by the CCSP report. These include the following upper-air variables and properties:

- Temperature
- Water Vapor
- Wind Speed and Direction
- Cloud Properties
- Earth Radiation Budget
- Changes in trace gas concentrations

Certain variables which the community identifies as of critical importance, such as temperature and humidity, would particularly benefit from more redundancy in their measurement. It is also important that the sites additionally measure surface parameters such as rainfall, albedo, emissivity, and soil moisture (among others) as certain applications, such as satellite radiative transfer, may require knowledge of these.

Reference sites would have the climate community as their primary customer. Therefore the strategy in setting up and maintaining the locations should follow the GCOS climate monitoring principles, which have been accepted internationally, both by the scientific community and governments, as parties to the Framework Convention on Climate Change.

It is recognized that the observing system at reference network stations may change over time with technological advances. Hence a key requirement of the reference network is sufficient overlap of systems (old to new) to maintain continuity over time, and full characterization of the accuracy and precision of new systems, preferably with traceability to SI standards. Benchmark observations, discussed above, would be a major advantage to the reference network in this critical respect. Regardless, measurements systems should be regularly calibrated at the site, where applicable. Furthermore, it is imperative that the network instrument replacement itinerary take into account changes in the comprehensive networks, such as satellites, to optimize its strategies. Such a strategy ensures that measurements are traceable back through time even if the absolute value is not known at the instigation of the network. Future measurement technology advances may then be able to be used to reverse-engineer absolute values.

Rather than having equal-area sampling it is important that a reference network capture the full range of climate regimes and surface types, providing reasonable latitudinal coverage. Radiative transfer codes used to convert raw satellite radiances to geophysical parameters depend upon assumptions about the surface conditions. Therefore, different local environmental conditions will need to be represented, including both land and ocean regions. It would also be advantageous to consider including in the reference network coincident special sites from existing research networks, such as the Atmospheric Radiation Measurement program, the Baseline Surface Radiation Network, the Global Atmosphere Watch, and the Network for the Detection of Stratospheric Change. It was agreed that an optimal network would be on the order forty locations (5% of the operational upper-air network) to fully capture this range of requirements allowing for a degree of redundancy in location types.

The reference network operations should be flexible enough to allow for intensive operations during field experiments to study climate processes. This includes a capability for high frequency sampling (e.g., every three hours). Furthermore, the reference network must be sustained by a high-quality support structure involving the facility and manufacturers of instrument systems.

Absolutely imperative to the success of a reference network will be a dedicated center that archives all data including data overlaps with observations from polar orbiters and other satellite measures such as GPS-RO and special field experiments. Although such a database would be maintained primarily for the climate community it is extremely likely to prove useful for non-climate applications. It is vital that the resulting database be freely available for bona fide research purposes by any interested parties in an easy to use format.

Along with the data it is critical to amass a comprehensive metadata archive. Experience shows that the data alone will be difficult to interpret without a comprehensive inventory of characteristics of instrument type and measurement and recording practices, obtained at a regular interval. The fixed (as opposed to expendable) instruments should be calibrated or tested against some reference standard, with a full report of the procedure being produced. Additional metadata would include regular surveying of the site (to facilitate identification of changes at the site or in the local area). For example, a (preferably digital) photo of the site, from different compass directions, and perhaps some sort of satellite imaging. This would provide a long-term, detailed history of land-use changes at the local site (eg: changes in exposure from growth or removal of vegetation) as well as in the surrounding area (urbanization). These high-temporal resolution, high detail metadata should be maintained by the same dedicated center that archives all of the data. The approach of requiring the reporting of a detailed inventory of instruments and practices *at a regular interval* will complement requiring a report when something changes and aid real-time monitoring efforts at the sites.

The role of aerosol measurements in the GCOS upper air reference network is likely to be necessarily limited due to the cost and complexity of making the measurements. A selected subset of the GCOS reference stations, covering a range of climatic regimes and dominant aerosol types (dust, smoke, pollution, etc.), should be co-located with GAW stations and equipped to measure a limited suite of aerosol properties at the surface and aloft. The role of these reference aerosol observations is to anchor global satellite observations and global chemical transport model calculations to well-calibrated measurements of key aerosol properties. At a minimum, the aerosol measurements should include the five core parameters recommended by GAW: optical depth, total mass concentration, mass concentration of major chemical species, light scattering coefficient, and light absorption coefficient. These measurements should be made continuously at the surface, and frequently enough aloft with a light airplane to capture synoptic-scale variability in aerosol properties (ca. twice weekly). Requirements for the measurements, based primarily on the NOAA Observing System Architecture requirements, are included in the tables below.

Workshop discussions on a reference network were limited primarily to the large-scale network design and purpose considerations discussed above rather than specific requirements for the monitoring of each variable. To progress further the series of requirements tables below have been completed and discussed by a cross-section of the climate community interested in the reference network issue before being distributed for wider consultation (including to all participants in the Boulder workshop). These tables are intended as a basis from which to move forward on the second workshop.

In the tables, each variable is given a priority ranking of 1, 2, 3, or 4, with 1 indicating the highest priority. Measurement ranges are meant to cover the ranges likely to be encountered over the vertical range of interest, so that any proposed instrument or set of instruments would need to be able to operate throughout that range. Measurement precision refers to the repeatability of the measurement, as measured by the standard deviation of random errors. However, measurement precision is closely tied to the frequency of observations, since observations are often averaged together, and the greater the sample size the less stringent is the required precision. We have not specified measurement frequencies because they may vary over time. However, for the highest priority variables, a program of two observations per day, every 2 or 3 days, would provide a reasonable climate record (Seidel and Free, submitted manuscript). Most instruments will be always on, it is mainly radiosondes for which this becomes important. Discussions with a number of satellite experts strongly imply that at least some radiosondes should be launched to coincide with polar orbiter overpass to really tie-down our uncertainties in satellite measures However, there was little time to build consensus regarding managing radiosonde launch schedules and the importance of retaining standard synoptic launch times. We stress that wholesale abandonment of synoptic radiosonde launch times is not being advocated at present. Ultimately radiosondes will prove to be the major expendable cost once a network site is set up.

Within the tables measurement accuracy refers to the systematic error of a measurement (the difference between the measured or derived value and the true value). It is not directly specified for many variables for which variations, and not absolute values, are needed to understand processes. However, it is directly related to the issue of long-term stability, which is a critical aspect of the reference network and which is specified in terms of the maximum tolerable change in systematic error over time. In other words, the effect on measurement error of any intervention to the measurement system, such as a change in instruments, should be smaller or quantified to a much greater degree than the value given for long-term stability, to ensure that realistic climate trends can be derived from the dataset. Long-term stability is a measure of the acceptable systematic changes on multi-decadal timescales. Of course, absolute accuracy would make the question of long-term stability moot, so where possible systems with absolute accuracy should be implemented. Where the expected climate change signals are known this has been specified so as to be an order of magnitude smaller than this expectation to avoid ambiguity as for example is evident in historical upper-air temperature records (Section 2.1).

Variable	Temperature	Water Vapor	Pressure
Priority (1-4)	1	1	1
Measurement Range	100-350 K	0.1 ppm to 55 g/kg	1 to 1100 hPa
Vertical Range	0 km to stratopause	0 to ~30 km	0 km to stratopause
Vertical Resolution	0.1 km (surface to ~30 km) 0.5 km (above ~30 km)	0.05 km (surface to 5 km) 0.1 km (5 to ~30 km)	0.1 hPa
Precision	0.2 K	0.1 g/kg in lower troposphere 0.001 g/kg in upper troposphere 0.1 ppm stratosphere	0.1 hPa
Accuracy	0.1 K in troposphere 0.2 K in stratosphere	0.5 g/kg in lower troposphere 0.005 g/kg in upper troposphere 0.1 ppm stratosphere	0.1 hPa
Long-Term Stability	0.05 K[1]	[1]1%	0.1 hPa
Comments	[1]The signal over the satellite era is order 0.1-0.2K/decade (Section 2.1.1) so long-term stability needs to be order of magnitude smaller to avoid ambiguity.	[1]Stability is given in percent, but note that accuracy and precision vary by orders of magnitude with height.	

Variable	Vector Wind
Priority (1-4)	2
Measurement Range	0 – 300 m/s
Vertical Range	0 km to stratopause
Vertical Resolution	0.05 km in troposphere 0.25 km in stratosphere
Precision	0.5 m/s in troposphere 1.0 m/s in stratosphere
Accuracy	1.0 m/s[1]
Long-Term Stability	0.5 m/s in troposphere 1.0 m/s in stratosphere
Comments	[1]to delineate calm conditions from light winds. Direction may be problematic under these circumstances.

Variable	Ozone	Carbon Dioxide	Methane
Priority (1-4)	2	3	2
Measurement Range	0.005-20 ppmV		
Vertical Range	Surface to 100 km		
Vertical Resolution	0.5 km in stratosphere 1 km in troposphere		
Precision			
Accuracy	3% total column 5% stratosphere 5% troposphere		
Long-Term Stability	0.2% total column 0.6% stratosphere 1% troposphere		
Comments			

Variable	Net Radiation	Incoming Shortwave Radiation	Outgoing Shortwave Radiation
Priority (1-4)	1	2	2
Measurement Range	0-1500 W/m2	0-2000 W/m2[1]	0-1365 W/m2
Vertical Range	Surface	Surface	Surface
Precision	5 W/m2[1]	3 W/m2[2]	2 W/m2[1]
Accuracy	5 W/m2[1]	5 W/m2[2]	3%[1]
Long-Term Stability	0.1 W/m2	0.1 W/m2	0.1 W/m2
Comments	[1]Accuracy and precision units from BSRN.	[1]Incorporates cloud reflection effects. [2]Accuracy and precision units from BSRN.	[1]Accuracy and precision units from BSRN.

Variable	Incoming Longwave Radiation	Outgoing Longwave Radiation	Radiances
Priority (1-4)	2	2	1
Measurement Range	0-900 W/m2	0-900 W/m2	Full spectral range 300-1700 cm^{-1} 190 K<T_b<330 K
Vertical Range	Surface	Surface	Surface to top of atmosphere. Need TOA upwelling and surface downwelling but not levels in between.
Vertical Resolution	N/A	N/A	N/A
Precision	1 W/m2[1]	1 W/m2[1]	0.01%
Accuracy	3 W/m2[1]	3 W/m2[1]	0.15%
Long-Term Stability	0.1 W/m2	0.1 W/m2	0.03% per decade
Comments	[1]Accuracy and precision units from BSRN.	[1]Accuracy and precision units from BSRN.	Stability requirement achievable through SI traceability; precision/accuracy requirement for mean seasonal radiances at ~1000 km spatial scale.

Variable	Aerosol Optical Depth	Total Mass Conc.	Chemical Mass Conc.
Priority (1-4)	2	2	2
Measurement Range	0.005 - 5	0.1-100 $\mu g\ m^{-3}$	0.1-30 $\mu g\ m^{-3}$
Vertical Range	Total column	0-6 km	0-6 km
Vertical Resolution	N/A	500 m	500 m
Precision	0.005	10%	10%
Accuracy	0.005	10%	10%
Long-Term Stability	0.005	10%	10%
Comments	Spectral measurements	Size-fractionated	Size-fractionated

Variable	Light Scattering	Light Absorption
Priority (1-4)	2	2
Measurement Range	0.1-1000 Mm^{-1}	0.1-1000 Mm^{-1}
Vertical Range	0-6 km	0-6 km
Vertical Resolution	500 m	500 m
Precision	10%	10%
Accuracy	10%	10%
Long-Term Stability	10%	10%
Comments	Size-fractionated, spectral	Size-fractionated, spectral

Variable	**Cloud Amount/Frequency**	**Cloud Base Height**	**Cloud Layer Heights and Thicknesses**
Priority (1-4)	2	2	2
Measurement Range	0-100%	0-20 km[1] (1000-50 mb)	0-20 km
Vertical Range	0 to 20Km	surface to 50 mb	Surface to 50mb
Vertical Resolution	50 m	5 mb	50 m[1]
Precision	0.1-0.3%[1]	100 m (10-40 mb[2])	50 m[2]
Accuracy	0.1-0.3%[1]	100 m (10-40 mb[2])	50 m[2]
Long-Term Stability	0.1-0.2%[2]	20 m/decade[3]	50 m/decade
Comments	[1]1-3% variations from ISCCP [2]1-2%/decade trend (Norris 2005)	[1] 1000-50mb (Rossow and Schiffer 1999) [2] 10-40 mb variations from ISCCP [3] 44/154 m/decade for base/top from Chernykh et al. (2001), which was questioned by Seidel and Durre (2002)	[1]the minimum layer thickness of ~30 m (cirrus) (Del Genio et al. 2002; Winker and Vaughan 1994) [2]the standard deviation of >= 100 m (Wang et al. 2000)

Variable	Cloud Top Height	Cloud Top Pressure	Cloud Top Temperature
Priority (1-4)	3	3	3
Measurement Range	0-20 km	1013-15 hPa	190-310 K
Vertical Range	0-20 km	0-20 km	0-20 km
Vertical Resolution	150 m	150m	1 km
Precision	50m	1 hPa	
Accuracy	150 m	15 hPa	1 K/(cloud emissivity)
Long-Term Stability	30 m	3 hPa	0.2 K/(cloud emissivity)
Comments			

Variable	Cloud Particle Size	Cloud Optical Depth	Cloud Liquid Water/Ice
Priority (1-4)	4	4	4
Measurement Range			
Vertical Range	0-20 km	0-20 km	0-20 km
Vertical Resolution	1 km	1 km	1 km
Precision			
Accuracy	10% water 20% ice	10%	25% water 0.025 mm ice
Long-Term Stability	2% water 4% ice	2%	5% water 0.005 mm ice
Comments			

3.4 Comprehensive Network

Under the "cascade of networks" concept, benchmark and reference observations provide highly accurate and stable observations to allow broad-scale assessments of climate change and variability. However, they do not provide the detailed spatial resolution necessary to relate climate change and variability to human activities and the environment. The main objective of the comprehensive component described in this section is to provide global measurements, linked to the benchmark and reference observations, that are needed for a variety of purposes, including monitoring large-scale and regional climate changes and variations, attributing the causes of climate change, predicting climate variability, and assessing climate impacts.

As indicated in Figure 14, the comprehensive network would contain at least the **baseline sites**, which have been termed the GCOS Upper Air Network (GUAN) stations not included in the reference network. The GUAN consists of 161 stations which GCOS has mandated (and relevant National Meteorological Services have agreed) be maintained as active upper-air monitoring sites. The coverage is designed to be sufficient to describe global and continental scale changes. Discussion of this network was limited during the workshop, but it is vital that we recognize the continued importance of this effort to maintain long-term continuous records into the future. Ongoing efforts to improve reporting frequency at these sites should be strongly encouraged.

In addition to GUAN observations, the comprehensive network includes a **composite** of observations, driven primarily by the needs of short-term forecasting, that is constantly evolving. By including many observing sites, instrument types (sonde, satellite, and in-situ) and networks, the comprehensive network provides the detailed spatial resolution necessary to relate climate change and variability to human activities and the environment. Because these networks answer primarily to weather forecast demands, they will be sub-optimal from a climate perspective without the benchmark and reference observations to provide transfer standards to account for the time-varying changes in observational network performance.

No specific requirements for the comprehensive network are given here, in part because the complexity and diversity of the network and its uses make it difficult to specify exact requirements. However, adherence to the GCOS monitoring principles will greatly aid the use of these observations in the future regardless of decisions regarding the smaller networks discussed above and their eventual success or otherwise. The comprehensive network contains multiple data types, including satellite data, and will increasingly rely strongly not only on network measurements but also on the synthesis and analysis of the observations, as described in Section 2.3. Although we recognize that the composite networks do not meet climate needs in many respects, they nevertheless have considerable value, and, as financial pressure increases to reduce the size of the in situ upper air network, the workshop felt a need to affirm the value of a comprehensive upper-air observing system from ground-, balloon- and satellite-based platforms.

4. SUMMARY

The NOAA/GCOS Workshop to Define Climate Requirements for Upper-Air Observations, that was held in Boulder, Colorado, on February 8-10, 2005, represented the first phase in a sequence of activities designed to define the scientific requirements for an upper-air observational network that will be adequate to meet climate requirements and to suggest technical options to meet these requirements.

The workshop focused primarily on observations of meteorological state variables (temperature, humidity, pressure, winds) in the troposphere and stratosphere. Some discussions also dealt with profiles of atmospheric constituents, stressing ozone and aerosols, but little attention was paid to regions above the stratopause.

This draft report, the fifth iteration prepared by the Workshop organizers, summarizes Workshop proceedings and recommendations. It has been revised following circulation to a broad list of interested parties, including all Boulder Workshop invitees, for review and comment. Following revision this final report serves as a primary planning document for the follow-on workshop in Seattle, currently planned for May 2006, and intended to propose specific technical solutions that could be employed to meet the stated scientific requirements.

Appendix A: Workshop Agenda

NOAA/GCOS Workshop to Define Climate Requirements for Upper-Air Observations
NOAA David Skaggs Research Center
325 Broadway, Boulder, Colorado

Tuesday, 8 February 2005
Morning Session - Chair: Sandy MacDonald

0730 Registration and Continental Breakfast

Setting the Stage

0830 Workshop goals - Chet Koblinsky
0845 Greetings from workshop hosts - Sandy MacDonald, Susan Avery
0900 Plans for achieving workshop goals and follow-on activities - Dian Seidel
0915 Introductions around the room
0920 Scientific Background – Mike Wallace
How have upper-air observations been used for climate research and monitoring?
What gaps limit the utility of the present observing system?
0940 What issues are driving the need for this workshop? - Rick Rosen
1000 Coffee Break

Related International and NOAA Activities

1030 Group on Earth Observations - Tom Karl
1050 GCOS implementation in support of the UNFCCC – Paul Mason
1110 GCOS Atmospheric Observation Panel for Climate activities – Peter Thorne
1130 US GCOS activities – Howard Diamond
1150 Lunch

Afternoon Session - Chair: Dave Hofmann
Requirements for monitoring and detecting climate variability and change

1300 Linkage between upper-air observations and NOAA's strategic plan;
Tropospheric and stratospheric temperature and humidity – Tom Karl
1340 Tropopause characteristics – Bill Randel
1410 Atmospheric composition – Sam Oltmans (ozone, etc.), John Ogren (aerosols)
1440 Atmospheric circulation - Jim Hurrell
1510 Coffee Break

Requirements for climate process studies and climate modeling

1530 Understanding feedback processes - Brian Soden
1600 Testing model parameterizations - Andrew Gettelman
1630 Evaluating climate models - Ants Leetmaa

1730 Workshop Reception – Science on a Sphere

Wednesday, 9 February 2005
Morning Session - Chair: Kevin Schrab

Requirements for satellites and radiative transfer models

0830 The importance of complementary upper-air observations for satellite remote sensing and their synergistic benefits - Mitch Goldberg

0900 Process studies to improve radiative transfer models - Bob Cahalan

Requirements for reanalyses and climate prediction

0930 Anchoring reanalysis and "around ongoing analysis" products – Phil Arkin

1000 Seasonal and interannual climate prediction – Jim Laver

1030 Coffee Break

Findings of related recent workshops

1050 "Emerging Science Applications of Measurements from GPS/GNSS and GPS-like Signals: Recent Results and Future Possibilities" - Jim Anderson

1110 "Utilization of Unmanned Aerial Vehicles for Global Climate Change Research" - Sandy MacDonald

NOAA Observing System Architecture

1130 Existing upper-air requirements for climate and guidance on refining them - Pam Taylor

1200 Lunch

Afternoon Session

1315 Breakout Groups: Gather information and discuss issues affecting requirements

Group #1 - Climate Monitoring, Chair: Neville Nicholls
Brief presentations by Melissa Free, Seth Gutman, Mark McCarthy, Sam Oltmans, Frank Schmidlin, Alex Sterin, June Wang, Betsy Weatherhead

Group #2: Climate Process Studies and Modeling, Chair: June Wang
Brief presentations by Alex Sterin, June Wang

Group #3: Satellites and Radiative Transfer Models, Chair: John Christy
Brief presentations by Dan Birkenheuer, Tony Reale

Group #4: Reanalyses and Climate Predictions, Chair: Randy Dole

1500 Coffee Break

1530 Breakout Groups: Prepare initial set of observational requirements

Thursday, 10 February 2005
Thursday Session - Chair: Chet Koblinsky

0830 Plenary: Breakout groups report on progress. Identify and resolve areas of confusion or conflict, within or between breakout groups
1000 Coffee Break
1030 Breakout Groups: Complete work on requirements
1200 Lunch
1315 Final plenary: Obtain consensus on requirements and workshop report outline
1600 Next Steps
1630 End of Workshop for all but drafting team

Friday, 11 February 2005

0800 Drafting team prepares workshop report
1200 Drafting team adjourns

Appendix B: Workshop Participants

Margot Ackley, NOAA Forecast Systems Laboratory
Jim Anderson, Harvard University
Phil Arkin, University of Maryland
John Augustine, NOAA Air Resources Laboratory
Susan Avery, University of Colorado
John Bates, NOAA National Climatic Data Center
Dan Birkenheuer, NOAA Forecast Systems Laboratory
Carl Bower, NOAA National Weather Service
Bob Cahalan, NASA
John Calder, NOAA Arctic Research Office
Russ Chadwick, NOAA/Forecast Systems Laboratory
John Christy, University of Alabama in Huntsville
Gil Compo, University of Colorado
Howard Diamond, NOAA National Climatic Data Center
Randy Dole, NOAA Climate Diagnostics Center
Tim Dunkerton, Northwest Research Associates
Imke Durre, NOAA National Climatic Data Center
Ellsworth Dutton, NOAA Climate Monitoring and Diagnostics Laboratory
John Dykema, Harvard University
Tim Eichler, NOAA Research
Joe Facundo, NOAA National Weather Service
Melissa Free, NOAA Air Resources Laboratory
Qiang Fu, University of Washington
Ken Gage, NOAA Aeronomy Laboratory
Mel Gelman, NOAA National Weather Service
Andrew Gettelman, NCAR
Mitch Goldberg, NOAA/NESDIS
David Goodrich, NOAA Office of Global Programs
Seth Gutman, NOAA Forecast Systems Laboratory
Colleen Hartman, NOAA/NESDIS
David Helms, NOAA National Weather Service
David Hofmann, NOAA Climate Monitoring and Diagnostics Laboratory
Jim Hurrell, NCAR
Tom Karl, NOAA National Climatic Data Center
Chet Koblinsky, NOAA Climate Office
Mike Kurylo, NASA Headquarters
Jim Laver, NOAA National Weather Service
Ants Leetma, NOAA Geophysical Fluid Dynamics Laboratory
Stephen Leroy, Harvard University
Sandy MacDonald, NOAA Forecast Systems Laboratory
Jerry Mahlman, NCAR
Paul Mason, University of Reading
Mark McCarthy, UK Met Office
Chris Miller, NOAA Office of Global Programs

Patricia Miller, NOAA Forecast Systems Laboratory
Ken Mooney, NOAA Office of Global Programs
Bill Murray, NOAA Office of Global Programs
Neville Nicholls, Australian Bureau of Meteorology
John Ogren, NOAA Climate Monitoring and Diagnostics Laboratory
Sam Oltmans, NOAA Climate Monitoring and Diagnostics Laboratory
Bill Randel, NCAR
Tony Reale, NOAA/NESDIS
Chris Rocken, NCAR
Rick Rosen, NOAA Research
Karen Rosenlof, NOAA Aeronomy Laboratory
Frank Schmidlin, NASA/Wallops
Kevin Schrab, NOAA National Weather Service
Dian Seidel, NOAA Air Resources Laboratory
Brian Soden, University of Miami
Susan Solomon, NOAA Aeronomy Laboratory
Alex Sterin, RIMHI
Pam Taylor, NOAA/NESDIS
Peter Thorne, UK Met Office
Russ Vose, NOAA National Climatic Data Center
Mike Wallace, University of Washington
Junhong Wang, NCAR
Betsy Weatherhead, NOAA Air Resources Laboratory
Robert Webb, NOAA Climate Diagnostics Center

Workshop Facilitators:

Facilitator Team Leader: Pamela Palanque-North, Palanque Associates
Keith Berger, NOAA National Weather Service
Lisa Darby, NOAA Environmental Technology Laboratory
Greg Gust, NOAA National Weather Service
Dick Felch, NOAA National Weather Service
Stanley Levine, NOAA National Weather Service
Annie Reiser, NOAA National Geophysical Data Center
Lisa Taylor, NOAA National Geophysical Data Center
Carmella Watkins, NOAA National Climatic Data Center

Local Arrangements:

Rhonda Lange, NOAA Forecast Systems Laboratory

Appendix C: Workshop Conveners, Steering Committee, Sponsors and Hosts

Workshop Conveners:

Rick Rosen, NOAA Assistant Administrator for Oceanic and Atmospheric Research
Greg Withee, NOAA Assistant Administrator for Satellite and Information Services
Mike Manton, Chair, Global Climate Observing System, Atmospheric Observations Panel for Climate

Workshop Steering Committee:

Howard Diamond, US GCOS Program Manager, NOAA/NCDC
Mitch Goldberg, Chief, Climate Research & Applications Division, NESDIS/ORA
Chet Koblinsky, Director, NOAA Climate Office
Sandy MacDonald, Director, NOAA Forecast Systems Laboratory
Bill Murray, NOAA/OGP Climate Change Data and Detection Program Element
Kevin Schrab, NOAA National Weather Service
Dian Seidel, NOAA Air Resources Laboratory
Peter Thorne, UK Met Office, Hadley Centre
Mike Wallace, Director, JISAO, University of Washington

Workshop Sponsors: The following offices provided financial, travel, and administrative support for the workshop and training for the members of the NOAA Facilitator Cadre who facilitated the meeting.

Global Climate Observing System (GCOS) Secretariat - http://www.wmo.ch/web/gcos/gcoshome.html

NOAA Office of Climate Observations - http://www.oco.noaa.gov

U.S. GCOS Program Office - http://www.eis.noaa.gov/gcos

NOAA/University of Colorado, Cooperative Institute for Research in Environmental Science - http://cires.colorado.edu/

NOAA Office of Diversity

Workshop Hosts: The workshop was graciously hosted by Dr. Sandy MacDonald, Director of the NOAA Forecast Systems Laboratory and by Dr. Susan Avery, Dean of the Graduate School and Vice Chancellor for Research, University of Colorado at Boulder.

Appendix D: Background Documents and References

A series of very useful background documents on climate requirements for upper-air observations are available in electronic form via the workshop web site, www.oco.noaa.gov/workshop. Additional references cited in this report are listed below.

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